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# Experimental investigation of laser peening on TiAl alloy microstructure and properties



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## KEYWORDS

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**Abstract** In order to study the effect of laser peening on microstructures and properties of TiAl alloy, TiAl alloy samples were treated by Nd:YAG laser system with the wavelength of 1064 nm, pulse-width of 18 ns, and pulse-energy of 0–10 J. Surface micro-hardness, roughness, and microstructural characteristics were tested with micro-hardness tester, roughness tester and scanning electron microscope. Residual stress and pole figures were tested with X-ray diffraction and its high-temperature stability was analyzed. The experimental results show that surface micro-hardness increases by up to 30%, roughness increases to 0.37  $\mu\text{m}$ , compressive residual stress increases to 337 MPa, and local texture and typical lamellar microstructure are generated. Residual stress, micro-hardness, and (002) pole figures tests are conducted, compressive residual stress value drops from 337 MPa to 260 MPa, hardness value drops from 377 HV<sub>0.2</sub> to 343 HV<sub>0.2</sub>, and the (002) poles shift back to the center slightly. Laser peening improves microstructure and properties of TiAl alloy significantly.

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## 1. Introduction

Much to the surprise of many engineers, compared with conventional shot peening,<sup>1</sup> high-pressure torsion,<sup>2</sup> laser

hardening,<sup>3</sup> water-jet peening,<sup>4</sup> and cold rolling<sup>5</sup> in terms of mechanical performance improvement, depth of compression layer and high level of stability,<sup>6</sup> laser peening is the most effective surface treatment method.<sup>7</sup> So, laser peening has been applied to a variety of alloys used in aircraft engines,<sup>8</sup> airframes<sup>9</sup> and other engineering applications,<sup>10–13</sup> to improve the damage tolerance of several critical compressor blade leading edges,<sup>14</sup> automotive parts,<sup>15</sup> orthopedic implants,<sup>16</sup> dies,<sup>17</sup> etc. It has been shown that laser peening causes beneficial microstructural changes in the material surface and thus improves component mechanical performance, for example,

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fatigue life of Ti17 titanium can increase up to 3 times,<sup>18</sup> the micro-hardness of 7075 aluminum alloys can increase up to 120%,<sup>19</sup> and compressive residual stress of TC4 titanium alloy can increase up to 500 MPa.<sup>20,21</sup>

For decades, two-phase  $\gamma$ -TiAl based alloys have received considerable attention for high-temperature structural applications in aerospace and automotive industries.<sup>22,23</sup> Plenty of studies have been conducted on the mechanical properties and microstructure evolution of these materials.<sup>24,25</sup> However, in the literature to date, few of it reports the effect of laser peening on microstructure and mechanical properties of TiAl alloy. Because laser shock peening method has potential to improve the mechanical properties of TiAl alloys, the present study is undertaken to develop a basic understanding of the effects of laser shock peening on the deformation microstructure, hardness, residual stress, and high temperature stability in a TiAl alloy. The results of all the characterization show the effectiveness of this processing method for inducing elastic and plastic deformation in TiAl alloy and the TiAl performance is improved.

## 2. Experimental method

TiAl alloy test samples bought from Institute of Metal Research Chinese Academy of Sciences (Shenyang, China) were used in this study. The TiAl alloy cast ingot was prepared by vacuum consumable treatment twice and vacuum induction melted treatment once with the chemical compositions being Ti-45.5Al-2Cr-2Nb-0.15B (see Table 1). The TiAl alloy samples was cut into small specimens with dimensions of 80 mm  $\times$  15 mm  $\times$  3 mm from the ingot which was treated by hot isotactic processing with the process parameters of 1300  $^{\circ}$ C, 150 MPa, and 3.5 h. Ambient temperature tensile test gave tensile strength of 805.4 MPa and yield strength of 715 MPa, and the microstructure of TiAl alloy is shown in Fig. 1. Prior to the peening process, the intended peening surfaces of specimens were grounded with 1200 grit sandpaper followed by final polishing to the surface roughness of 0.05  $\mu$ m, and were treated by stress relieving device from Huayun Inc. (Jinan, China) with process parameters of 40 kHz, 50  $\mu$ m and 5 min to eliminate stress of specimens' surface.

Laser peening was carried out with self-developed laser peening system (see Fig. 2) with pulse energy  $K$  of 0–10 J, wavelength of 1064 nm, pulse duration (full width at half maximum, FWHM) of 18 ns, and frequency of 2 Hz. The laser beam which comes from lasers travels through optical microscope, homogenized microscope and focusing lens and then irradiates onto a material surface with a square laser beam spot, whose side length is 3 mm and the laser intensity is shown in Table 2. In the laser peening experiment, the dark tape (thickness of 100  $\mu$ m) from 3M Inc. (Shanghai,

China) was used as an ablative medium to protect the sample from thermal effects and deionized water (thickness of 2 mm) was used as confining medium. The track paths schematic of laser peening are shown in Fig. 3 and the overlap ratio of laser beam spot was 50%.

The micro-hardness of the samples before and after laser peening was measured using a FM-300 micro-hardness tester from Future-tech Inc. (Japan), with load of 200 g and holding time of 10 s; an average of five measurements was used for each test point. The surface roughness of the sample before and after laser peening was tested using a MicroXAM-1200 optical profiler from KLA-Tencor Inc. (Shanghai, China). Grain orientation pole figures before and after laser peening were obtained with D/maxIA X-ray diffraction device from Rigaku Inc. (Japan). Residual stress before and after laser peening was determined using the fixed inclination  $\psi$  method by Proto-LXRD X-ray diffraction device from Proto Inc. (Canada), and the diffraction conditions were listed in Table 3. To investigate the thermal stability, the samples were put in a furnace for

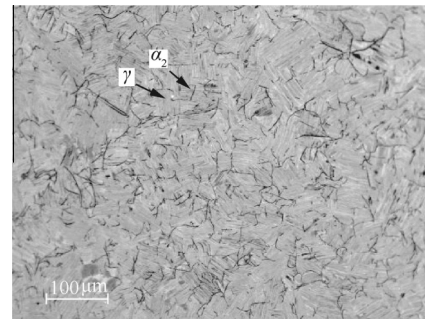


Fig. 1 Microstructure of TiAl alloy.

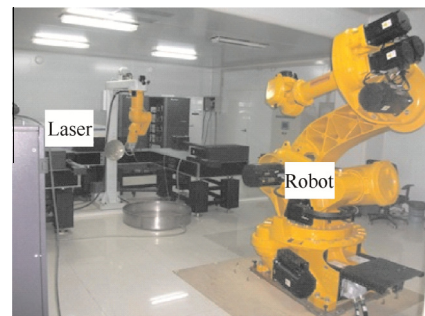


Fig. 2 Self-developed laser peening system.

Table 1 Chemical compositions of TiAl alloy.

Element	Al	Cr	Nb	B	O	N	H	Ti
wt%	31.3	2.69	4.88	0.04	0.072	0.013	0.003	Bal.

different heat treatment time with a temperature of 700 °C by furnace from BSK Inc. (Luoyang, China). To obtain the interior residual stress, the material was removed layer by layer by an electrolytic polisher from Proto Manufacturing Inc. (Canada); the electrolytic polishing medium was the  $\text{Na}_2\text{SO}_4 + \text{H}_2\text{SO}_4$  solution. Microstructure was observed by S-3400N scanning electron microscope and the etching medium was the  $\text{Na}_2\text{SO}_4 + \text{H}_2\text{SO}_4$  solution.

### 3. Results and discussion

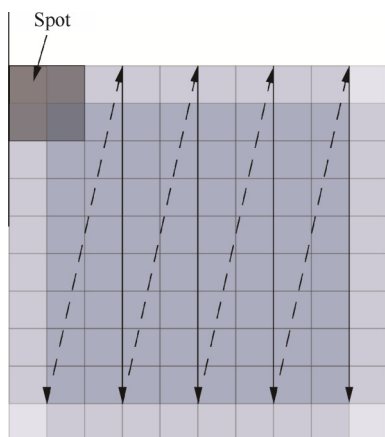
#### 3.1. Effect of laser peening on surface roughness and morphology of TiAl alloy

Fig. 4 shows the surface roughness of laser peened region with different laser pulse energy. The peened TiAl alloy surface is

slightly rougher than the original TiAl alloy surface. We also find that the roughness data increases with the increase of laser peening times. After being laser peened, the roughness increases from 0.05  $\mu\text{m}$  to 0.37  $\mu\text{m}$  with laser pulse energy of 9 J peening for 3 times. From Fig. 4, we also find that roughness approximately increase linearly with the increase of laser pulse energy, while slowly increases with the increase of laser peening times. These results come from the increase of plastic deformation capacity which is induced by the increasing laser pulse energy and laser peening times, because the peak pressure of shock wave which is induced by laser peening increases with the laser pulse energy, the depth and amounts of micro-dents which is introduced onto the surface of TiAl alloy by laser peening increase with the increase of the peak pressure of shock waves and laser peening times, and the depth difference of micro-dents does not increase with increasing laser peening times and overlapping ratio dramatically. The increase of roughness is unfavorable for the fatigue life of components, so we need to control the roughness increase in a reasonable range. After being laser peened, the TiAl alloy samples' roughness is no more than 0.4  $\mu\text{m}$ , which is suitable for working requirements of aeroengines, because the roughness should be less than 0.8  $\mu\text{m}$  in aeroengine.

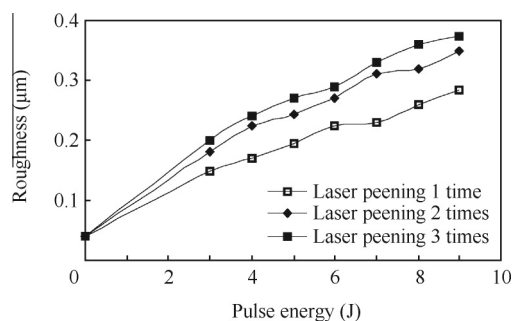
Fig. 5 shows the surface morphology of laser peened region with overlapping ratio of 50%. When laser pulse energy is more than 3 J, lots of micro-dents and micro-convexities are generated after laser peening treatment, because the plastic deformation is introduced into TiAl alloy surface by high-pressure shock waves. The amounts of micro-dents and micro-convexities also become more and more with the increase of laser peening times. The changes of micro-dents depth and micro-convexities height is the same as the micro-dents and micro-convexities' quantity. However the maximum depth of micro-dents and the maximum height of micro-convexities do not increase slightly at relatively high laser pulse energy (about 6–9 J), because the deionized water which is used as confining medium water is maybe ionized and broken down by the higher laser pulse energy. The ionized and breakdown water absorbs most of the laser pulse energy which outputs from laser system, so there is only a small part of laser beam which can be through the ionized and breakdown water, and irradiates onto the ablative layer on the TiAl alloy surface, so the shock wave energy is not increased slightly. These micro-dents are very useful for wear resistance, because the lubricating oil which present in the dents can provide a stable oil film for rolling friction and sliding friction.

Laser energy (J)	Laser intensity ( $\text{GW}/\text{cm}^2$ )
3	1.7
4	2.3
5	2.8
6	3.4
7	3.9
8	4.5
9	5.5

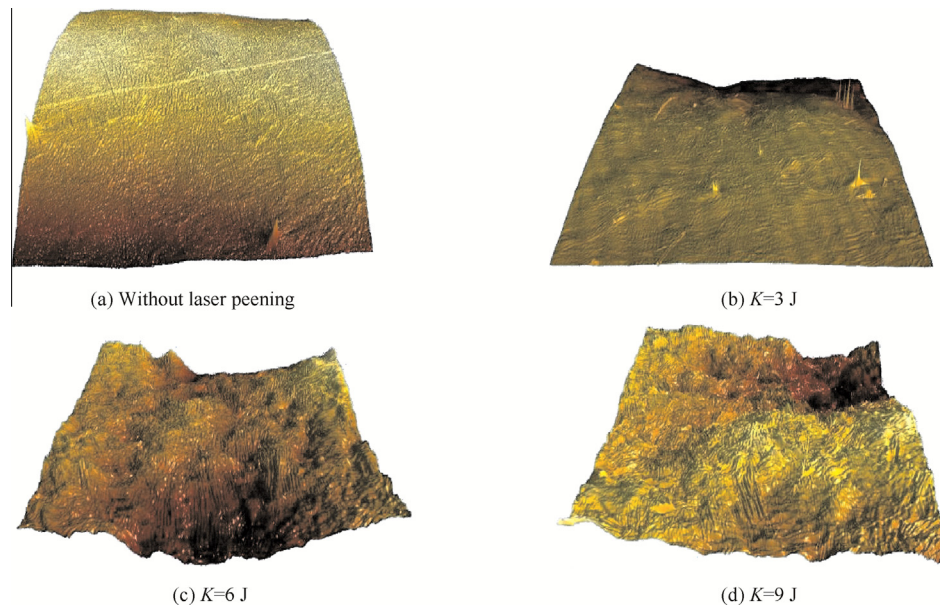


**Fig. 3** Track paths' schematic of laser peening.

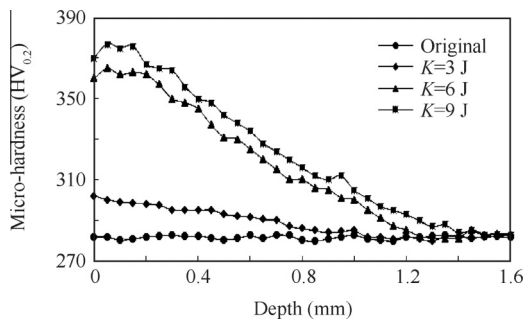
Parameter	Description
X-ray tube	Ti-K $\alpha$
Diffraction plane	(202)
Voltage (kV)	25
Current, $I$ (mA)	25
Angle ( $^\circ$ )	$\pm 5$
Method of peak position determination	Half-maximum intensity
Spot, $D$ (mm)	3



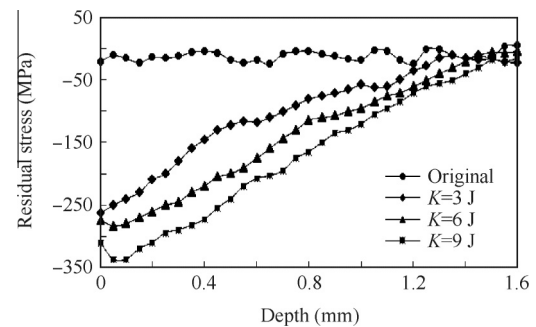
**Fig. 4** Effect of surface roughness on pulse energy.



**Fig. 5** Laser shock peened surface topography maps.



**Fig. 6** Micro-hardness distribution on cross-section.



**Fig. 7** Residual stress distribution on cross-section.

### 3.2. Effect of laser peening on surface micro-hardness of TiAl alloy

The micro-hardness distribution on TiAl alloy section is measured before and after laser peening (see Fig. 6). From Fig. 6, we can find that laser peening could improve micro-hardness onto the TiAl alloy surface, because plastic deformation, high density dislocations, and fine grain are induced on the material surface by high-pressure shock waves. According to the dislocations reinforcement theory, generation and motion of dislocations can lead to the work hardening, and the Hall–Petch theory illustrates that the yield stress increases with reducing grain diameter. At laser pulse energy of 3 J, micro-hardness is higher than that of the original material by approximately 6%, which is not improved significantly. When laser pulse energy is over 6 J and 9 J, micro-hardness is found to be approximately 30% higher than that of the original material. But when laser pulse energy is over 6 J, it does not continuously substantial increase, and a maximal micro-hardness of 377 HV<sub>0.2</sub> is achieved at 9 J. The reason lies in that plastic deformation and grain refinement gradually reach saturation

with the increase of the maximum peak pressure of shock wave. Fig. 6 also shows that the affected depth could reach 1.4 mm, and the micro-hardness gradually decreases to original material micro-hardness from surface to inside, because the high peak shock wave strength weakens with the increase of depth, and only when peak pressure of the shock wave exceeds dynamic yield stress of the substrate (Hugoniot elastic limit), the material generates plastically deformation.

### 3.3. Effect of laser peening on surface residual stress of TiAl alloy

In laser peening, the surface of the material is shocked by high-pressure peak shock wave, often resulting in compressive residual stresses being produced at surface and sub-surface of the material. The maximum compressive residual stress value usually appears at some depth below the surface. Fig. 7 illustrates residual stress distribution on TiAl alloy cross-section with different laser pulse energy (3, 6, 9 J), laser peening can induce high-amplitude compressive residual stresses with a deep affected layer, resulting from the lattice distortion, such as



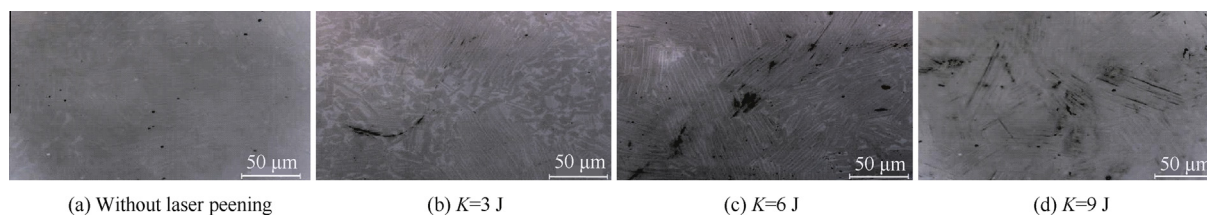
dislocations, fine grain and new grain boundaries. The maximum magnitude of compressive residual stress in laser peened material is discovered in the sub-surface region, about 80  $\mu\text{m}$  below the surface. The thickness of compressed surface layer in laser peened material is found to be about 1.4 mm. The compressive residual stresses are found to increase with the increasing of laser pulse energy. Compressive residual stresses increase from 15 MPa to 337 MPa after laser peening with parameters of 9 J and 18 ns.

From Fig. 7 we also find that compressive residual stresses increase slowly when laser pulse energy is more than 3 J, resulting from the increasing plastic deformation induced by the increasing peak pressure of shock wave and duration time of laser pulse. In depth, the value of compressive reduces gradually, because the propagation of shock wave in material can be absorbed with the increase of depth. The kinetic energy of high pressure shock wave is consumed and absorbed, which mainly transforms into dislocation and plastic deformation energy on the surface and sub-surface. So with the depth increasing, less and less plastic deformation is generated, therefore compressive residual stress decreases on the section of TiAl alloy. Therefore, the ultimate reason of the compressive residual stress distribution is that the peak pressure of shock wave decreases, with

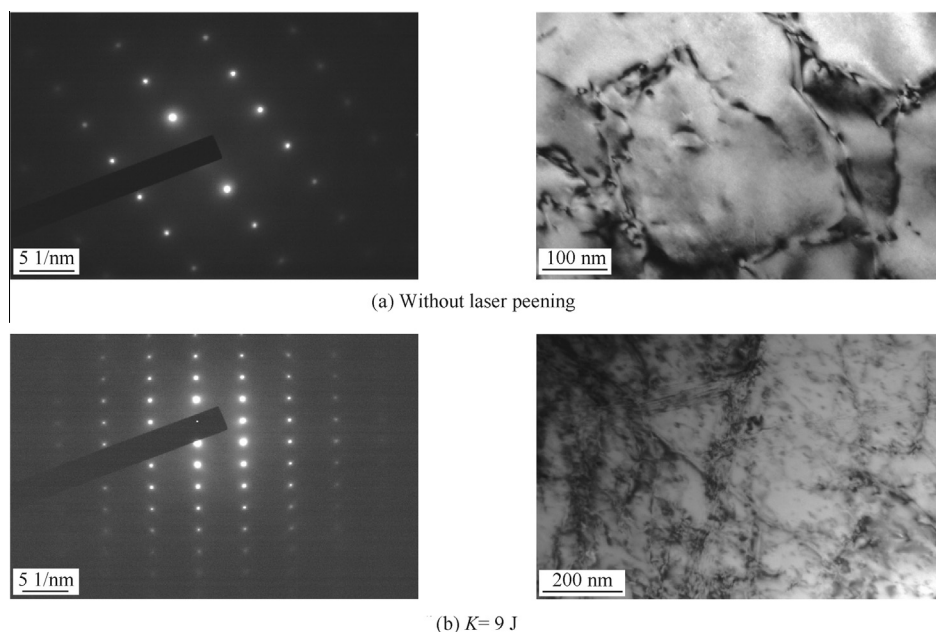
the propagation of shock wave. The relationship between surface compressive residual stress and laser pulse energy is similar to the relationship between surface micro-hardness and laser pulse energy. The connection between the micro-hardness and compressive residual stress lies in the grain refinement and plastic deformation induced by laser peening.

### 3.4. Effect of laser peening on microstructure of TiAl alloy

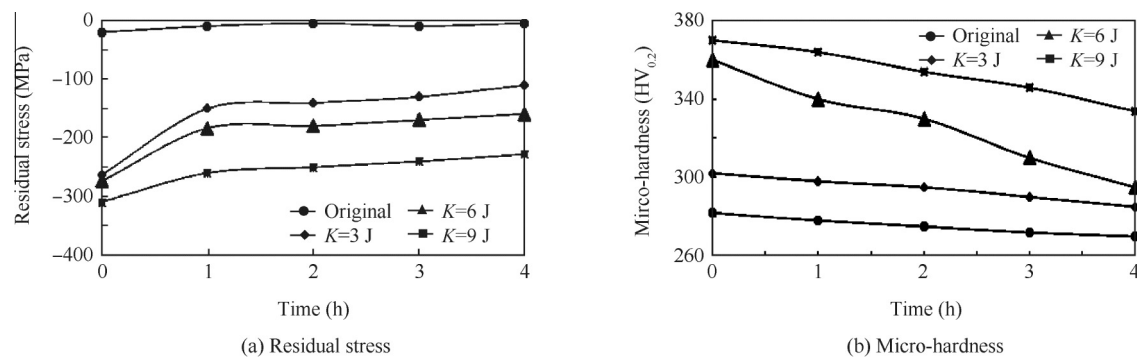
Fig. 8 shows the surface microstructure of original and laser peened samples. Original sample has smooth surface, while the peened samples show typical microstructure of TiAl alloy, of which the typical lamellar microstructure and local texture can be found on the peened surface from higher magnification pictures. The higher laser pulse energy, the more lamellar structure can be seen on the peened surface, which results from the peak pressure of shock wave induced by pulse laser which irradiated on ablative material surface. During laser peening, the peak pressure of shock wave is more than several or tens of Giga Pascal, which is far greater than the dynamic yield strength of TiAl alloy; dislocations, slippage, grain refine and plastic deformation are generated under the effect of high pressure shock wave,



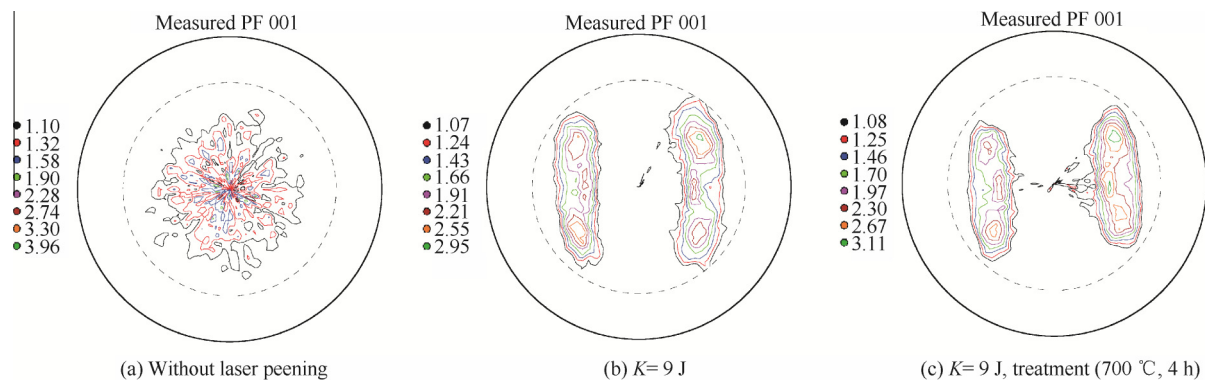
**Fig. 8** Surface microstructure of original and laser peened samples.



**Fig. 9** Bright-field TEM image of original and laser peened samples.



**Fig. 10** Effect of thermal stability on treatment time(700 °C).



**Fig. 11** Pole figures of TiAl (002) plane.

which results in changes of crystal orientation, lattice distortion, dislocation multiplication, dislocation slippage, twins, and other crystal defects. As the laser pulse energy increases, the amount and density of dislocations increase, thereby the local texture and lamellar are produced, which satisfies the previous residual stress analysis.

To examine the nature properties of the work-hardened surface layer for the laser peened surface condition, TEM characterization is shown in Fig. 9. The original features of the sample are very regular. However, after laser peening, the microstructure is characterized by regions of heavily tangled dislocations, dislocations walls, twins, and refined grains, which indicate that high density dislocations and dislocation cells are generated by laser peening. Fig. 9 also shows that crystal defects such as high density dislocation, dislocation cells, new boundaries, and sub-boundaries are produced on the surface of TiAl alloy, dislocation cells are large and have thin walls composed of tangled dislocations, the grains have been refined and the size reaches the nanometer scale, about 120 nm. The microscopic structure transformation at the hardened layer will play an important role in improving mechanical performance, and the mechanism is that laser peening produces fine crystals and sub-grains, and the boundaries enhance the resisting force of slipping and the crack expansion.

### 3.5. Thermal stability of laser peened surface

Compressive residual stress and micro-hardness of laser peened region with different heat treatment time are shown in Fig. 10. At elevated temperatures up to 700 °C, laser peening is found to result in extended compressive residual stress and micro-hardness, although the effect is smaller than at ambient temperature. This indicates that compressive residual stresses and micro-hardness are clearly more stable on the surface and near-surface at elevated temperatures. Compressive residual stresses, measured using X-ray diffraction, are shown in Fig. 10 for the laser peening samples as a function of heat treatment time of 1, 2, 3, 4 h. With heat treatment, there is some degree of relaxation at all temperatures and compressive residual stress values are only reduced to 150 MPa at 700 °C for 4 h. The stability of these strengthened surface layers can be confirmed by micro-hardness measurement results, and surface micro-hardness values are only reduced to 340 MPa at 700 °C for 4 h. This results from relaxation of the plastic deformation and high density dislocation on material surface introduced by laser peening and refined grain is stable.

The microstructure of the material after laser peening and controlled heat treatment is shown in Fig. 11, and the original (002) texture of virgin sample shows a higher distribution at the center. After laser peening, the (002) poles orientation angle

are shifted to larger, and the grain orientation becomes more dis-oriented. After laser peening and 700 °C for 4 h heat treatment, the (002) poles shift back to the center. This results from the reduction of crystal orientation, lattice distortion, dislocation multiplication, dislocation slippage, twins, and other crystal defects. The pole figures' change is satisfied with the residual stress and micro-hardness on heat treat time. So the laser peening mechanisms are grain refinement and residual stress enhance. At elevated temperature, residual stress would be some degree of relaxation, but the grain would not grow big obviously.

#### 4. Conclusions

The surface morphology, micro-hardness, compressive residual stress, and thermal stability of TiAl alloy, treated by laser peening are investigated, and laser peening improves microstructures and properties of TiAl alloy significantly. The following conclusions can be drawn:

- (1) Laser peening could improve the surface micro-hardness. Micro-hardness improves with the increase of laser pulse energy; when the laser pulse energy is more than 9 J, the maximal surface micro-hardness improves by more than approximately 30%, and the depth of hardened layer is more than 1.4 mm.
- (2) Laser peening could improve the surface roughness. Roughness increases with the increase of laser pulse energy; when the laser pulse energy is 9 J, the maximal surface roughness increases to 0.37  $\mu\text{m}$ .
- (3) Laser peening could improve the surface compressive residual stress. Compressive residual stress increases with the increase of laser pulse energy; when the laser pulse energy is 9 J, the maximal compressive residual stress increases to 337 MPa, and the depth of compressive residual stress layer is more than 1.4 mm.
- (4) The micro-hardness, compressive residual stress, and microstructure introduced by laser peening has higher stability. After laser peening with laser pulse energy of 9 J, the micro-hardness remains stable during high temperature up to 700 °C for 4 h, and there is only a slight decrease. Dislocation moves back slightly.
- (5) Texture evolution can be found in the laser peened samples.

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